AN OVERVIEW ON THE MATERIALS AND MECHANICAL BEHAVIOR USED IN FUSED DEPOSITION MODELING

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Abstract

Additive manufacturing offers significant opportunities for the production of final parts and products. Fused deposition modeling is a polymer additive manufacturing process widely used to build unreinforced and fiber-reinforced thermoplastic parts using the principle of extrusion. This work aims to review the state-of-the-art of fused deposition modeling by discussing the main advantages and limitations of the process. The building and processing parameters and their influence on mechanical behavior are addressed. A lack of understanding of these relevant parameters was identified. This literature review has shown that a deeper understanding of processing and material properties is needed to enable fused deposition modeling to become a standard manufacturing process in core industries.

Introduction

The investigation of new manufacturing technologies is a key factor for success for core industries, such as automotive and aerospace. This is an important step for developing efficient products, such as lightweight vehicles to decrease fuel consumption.

Additive manufacturing (AM) is one of these innovative techniques. Although a manufacturing technology in evidence, AM is a relatively old process developed in the 1980s [1]. The broad use of the term AM implies the opposite meaning to subtractive technique, whereby the material is added layer by layer to form a final part. According to ASTM F2792-12a [2], AM has other available synonyms, for instance, generative manufacturing, rapid prototyping, 3D printing, among others. Table 1 divides AM into four categories: (1) liquid-, (2) powder-, (3) solid- and (4) gas-based AM. The detailed description of each process is available in the work from Kruth et al. [3]. There are different methods of building a 3D part. The techniques differentiate themselves by the process of adding successive layers. For example, ink jet printing operates depositing ink droplets through a fine orifice [4], while selective laser sintering melts polymer powder to build the part [5]. The fused deposition modeling (FDM), a widely applied polymer AM technique, uses thermoplastic feedstock in form of a filament. The thermoplastic feedstock is heated to temperatures above its melting point for semi-crystalline, or above glass transition temperature for amorphous thermoplastics. The molten material is deposited layer by layer to create an end part.

Table 1. Short list of additive manufacturing processes for polymers. Adapted from Kruth et al. [3]

<table>
<thead>
<tr>
<th>Supply</th>
<th>Process</th>
<th>Material addition method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid</td>
<td>Ink jet printing (IJP)</td>
<td>Drop-on demand deposition</td>
</tr>
<tr>
<td>Powder</td>
<td>Selective laser sintering (SLS)</td>
<td>Layer of sintered powder</td>
</tr>
<tr>
<td>Solid</td>
<td>Fused deposition modeling (FDM)</td>
<td>Continuous extrusion and deposition</td>
</tr>
<tr>
<td>Gas</td>
<td>Selective laser chemical vapor deposition</td>
<td>Condensation of gas</td>
</tr>
</tbody>
</table>

State-of-the-art studies have mainly reported on the evaluation of process parameters, such as the influence of air gap on the strength and stiffness of the final part [6–8]. A few works reported that the mechanical performance of the AM part is significantly affected by the road angle [8, 9], road orientation [10, 11] and road width [12].

Moreover, other researchers [13–16] have focused on the development of new filament materials, including the incorporation of reinforcing fibers to improve the mechanical properties of FDM parts, or on the addition of metal particles (e.g. to mimic a metallic surface finishing)
New FDM materials have been constantly developed and launched into the market, such as high-performance engineering thermoplastics (e.g. polyether ether ketone, PEEK). MarkForged has recently released FDM 3D-printers able to print discontinuous and continuous fiber-reinforced materials, including carbon-, glass- and aramid-reinforced filaments [18].

This paper aims to address the main features and building parameters of the FDM process reported in the literature. Moreover, a systematic review of the main materials applied in this technique is presented, followed by the description of building parameters and their influence on the part’s mechanical properties.

**Fused deposition modeling**

Since 2013, the FDM technology has faced a steep growth associated with the expiration of the original technology patent held by Stratasys [19]. The technology is changing the standard fabrication methods used in the traditional manufacturing industry. A recent case study comes from the German automotive company BMW. By implementing FDM using acrylonitrile butadiene styrene (ABS) in substitution to traditional CNC methods for machining Aluminum parts, the car manufacturer was able to improve assembly line productivity and reduced part costs up to 60% [20].

**Process principles**

FDM is a polymer additive manufacturing technology able to produce parts with complex geometries by depositing extruded material layer by layer in a substrate (also known as printing bed). A representation of the process is depicted in Figure 1. The main components of a FDM machine are: (1) extrusion head, (2) build platform and (3) material spool (or filament). The main parts of the extrusion head are: drive wheels, heating element and extrusion nozzle [21].

The base material is available as a flexible filament, which is fed through a heating element in the extrusion head, where a nozzle with resistive heaters is located. These components are responsible for softening or melting the polymeric filament at high temperatures (above $T_g$ or $T_m$) decreasing material viscosity [22]. Thus, the softened or molten material flows easily through the extrusion nozzle consolidating to form the first deposited layer. The subsequently added layers will weld onto previously printed material. Usually, the FDM extrusion head is operating in the x-y plane, while the building platform moves down in the z-plane to accommodate the deposit layers until the whole 3D part is finished [23].

FDM undergoes similar steps as found in any other additive manufacturing process. Firstly the information from a CAD file is taken. This file has all the data in a 3D space which is converted into a STL (Standard Triangle Language) file in the following step. In other words, during STL transformation, the 3D-CAD model is approximated to a group of triangles. Subsequently, the AM process translates the 3D-STL model into the digital information required to build the 3D object layer by layer until the end part is completed [22].

The desired 3D part can be manufactured with a variety of materials because the filament can be exchanged or combined to form a multi-material part. Moreover, FDM requires no filler or catalytic material, post-processing, or expensive equipment. FDM also requires only fewer building parameters to achieve high finishing quality. The nozzle diameter and the movable building platform influence the road thickness, which can vary from 0.2 to 0.4 mm [24]. Furthermore, Görski et al. [25] identified that the overall dimension variability of FDM parts is 2%, similar to other polymer AM technologies (for example, the stereolithography with 2.3% dimension variability [26]). Gurrala et al. [27] reported that shrinkage can be minimized by changing part’s building orientation. Other FDM parameters have also been reported to positively influence part surface quality, such as longer printing times, thicker roads and road angle (0°/90°) among others [28, 29]. Besides the part’s surface quality and dimensional accuracy, these parameters have a significant effect on the final mechanical properties. The correlations between this process parameters and mechanical properties will be discussed in more details in the next section. Equally important is the presence of air gaps, also known as voids or internal flaws, which are intrinsic to the process and related to the circular cross section of the deposited filament. These voids may act as local stress concentrators in FDM parts, decreasing the global strength of the additively manufactured component in comparison to injection molded parts [30, 31].

![Figure 1. FDM process and main equipment components](image-url)
Process parameters

A number of studies have considered that the road angle \[8, 9\], road orientation \[10, 11\], road width and thickness \[12\] and air gap \[6, 8, 30, 31\] play a significant role in the global mechanical performance of FDM parts. A short description of each geometrical parameter is summarized below and graphically shown in Figure 2:

i. **Road**: a single pass of extruded filament. This parameter is controlled by the extrusion nozzle diameter and deposition rate.

ii. **Road width**: refers to the width of the deposited filament used to build the part.

iii. **Road thickness**: the thickness of the deposited layer.

iv. **Road orientation**: also known as build strategy, this parameter is associated with build orientation in the print bed.

v. **Road angle**: the direction of filament deposition relative to the x-axis of the build platform.

vi. **Air gap**: is the gap between the roads on the same layer.

Current efforts in FDM process development are concentrated in improving and optimizing the manufacturing routes. These include the optimization of processing time, building strategies, effects of road properties and orientation on the surface finishing and mechanical properties, and production time of FDM parts \[28, 31, 13\].

Figure 2. Representation of the main process parameters in FDM. Adapted from Bagsik et al. \[32\]

Table 2 summarizes a list of the common parameters divided into three categories based on (1) material, (2) geometry and (3) operation. The operation and geometry parameters can be easily adjusted; they play a significant role on the mechanical performance and quality of the final part. According to Agarwala et al. \[13\], geometry and operation parameters can be, for instance, set to eliminate void spacing on one hand. On the other hand, the material parameters are associated to characteristics of the materials and can be only influenced by selecting new filaments fulfilling the desired part requirements.

<table>
<thead>
<tr>
<th>Material</th>
<th>Geometry</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of expansion</td>
<td>Support structure</td>
<td>Flow rate</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>Road angle</td>
<td>Nozzle diameter</td>
</tr>
<tr>
<td>Glass Transition and Melting Temperatures</td>
<td>Road orientation</td>
<td>Extrusion head speed</td>
</tr>
<tr>
<td>Molten viscosity</td>
<td>Road width</td>
<td></td>
</tr>
<tr>
<td>Stiffness</td>
<td>Road thickness</td>
<td></td>
</tr>
</tbody>
</table>

The extruded material is deposited as a thin layer. The road width and road thickness are defined by the operation system. As the filament is heated up to a temperature above the \(T_g\) or \(T_m\), the material flows, in a certain extension, perpendicularly to the deposition direction and consolidates. The dimensions of the deposited layer are therefore controlled by the material flow rate. The dimensions of the road, e.g. thickness and width, along with the extrusion head speed, determine the flow rate of the extruded material \[33\].

The road orientation needs to be defined based on the motion of the extruder head relative to the loading carrying direction of the part. Error! Reference source not found. shows three types of road orientation for layer filling: (a) road fill, (b) contour fill and (c) contour with road fill. Road fill is used when high extrusion head speeds and flexibility to change road direction in adjacent layers are necessary. In contour fill modus the extrusion head follows loop contour motions inside a predetermined region. The contour with road fill pattern is a combined approach from the first two methods. This approach can reduce the amount of air gap by decreasing the space between the layers and adjacent road \[31, 34\].
Table 3 shows examples of three common materials used in FDM and their significant properties. ABS - an amorphous thermoplastic used in several consumer products [6] - is the most common material used. An example of an engineering amorphous thermoplastic is the polyetherimide (PEI). Thanks to its high glass transition temperature (e.g. PEI ULTEM grade 9085 with $T_g = 186^\circ C$), PEI has an outstanding ultimate tensile strength (71 MPa) and elastic modulus at room temperature (2.2 GPa) [39]. Polyether ether ketone (PEEK) is a semi-crystalline thermoplastic with great potential as FDM material. It has a wide range of attributes, such as high ultimate tensile strength (103 MPa [40]) and outstanding thermal stability up to 250°C [41].

<table>
<thead>
<tr>
<th>Properties</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ABS[36]</td>
</tr>
<tr>
<td>$E$ [GPa]</td>
<td>2.4[6]</td>
</tr>
<tr>
<td>$UTS$ [MPa]</td>
<td>26[6]</td>
</tr>
<tr>
<td>$T_g$ [°C]</td>
<td>94</td>
</tr>
<tr>
<td>$T_m$ [°C]</td>
<td>n/a</td>
</tr>
<tr>
<td>$T_{ext}$ [°C]</td>
<td>270</td>
</tr>
</tbody>
</table>

$E$ - Tensile modulus
$UTS$ - Ultimate tensile strength
$T_g$ - Glass transition temperature
$T_m$ - Melting temperature
$T_{ext}$ - Extrusion temperature

**Mechanical behavior of FDM materials**

A limited amount of studies has evaluated the influence of built strategies on the mechanical performance of FDM parts. The effects of road angle and orientation were studied by Bellini et al. [42]. Other authors [9, 28, 29] evaluated the influence of process parameters on defect formation, and its correlation to part strength. They reported that the major process parameters influencing part quality are road thickness, road angle, road width and air gap.

Figure 4 shows the work of Ahn et al. [6] on FDM ABS specimens. It is possible to observe that FDM parts have lower quasi-static strength in comparison to injection molding. This figure also shows the effect of negative air gap increases (“Zero air gap”) on the part density. The higher the zero air gap, the stronger is the part, as part density increases. Furthermore, the orientation $[0^\circ /90^\circ]$.

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**Materials used in FDM**

Thermoplastic materials are commonly used in FDM and can have many industrial applications. With the advance of materials development and the FDM process, the technology has been increasingly extended to several engineering thermoplastics and advanced engineering materials.
exhibited a large increase in tensile strength in comparison to $[-45^\circ/45^\circ]_6$.

Figure 4. Tensile strength of ABS FDM parts with different road orientations along with the average value of injection molded reference specimens. Adapted from Ahn et al. [6]

Fatimatuzahraa, Farahaina and Yusoff [31] obtained similar mechanical strength results for FDM ABS parts in comparison with Ahn et al. [6]. Moreover, they studied the influence of FDM ABS parts under bending (Figure 5) and impact loading (Figure 6) [31]. The authors reported that the addition of 90$^\circ$ layers parallel to the applied load, lowered the flexural strength in the cross-ply configuration in comparison to the angle ply configuration (see Figures 5 and 6). The angle ply has the contribution of the overlapping pair layers $+45^\circ$ and $-45^\circ$, which increases part’s capability of carrying bending loads.

Figure 5. Bending test results for ABS cross ply and angle ply FDM specimens. Adapted from Fatimatuzahraa, Farahaina and Yusoff [31]

Another interesting observation was reported by Pan et al. [43]. They studied the influence of the deposition speed and road thickness on the strength of polylactic acid (PLA) parts. The authors concluded that increases in deposition speed and road thickness improve the parts’ tensile strength. They reported that bonding strength is relatively lower for thin road thicknesses (e.g. 0.1 mm) when combined with slower deposition speeds (e.g. 30 mm/s) than with higher deposition speeds (e.g. 60 mm/s). The authors refer to the better intermolecular diffusion at higher deposition speeds.

Ning et al. [15] studied the effect of process parameters, such as deposition speed and road thickness, in 5 wt% short carbon fiber reinforced ABS. Figure 7 shows the deposition speed within a range of 15 mm/s to 35 mm/s and its effect on yield strength, elastic modulus and tensile strength. The mechanical properties reached a maximum at 25 mm/s, whereby further increases in deposition speed had negative effects on the properties. One can observe that the higher the deposition speed, the shorter the deposition time will be which results in weaker interlayer bonding between the adjacent roads. Moreover, Ning et al. [15] evaluated the influence of road thickness (Figure 8) on part’s tensile strength. According to the authors, the reason for the reduction in mechanical properties with increasing road thickness is associated with the poor interlayer bonding consolidation. 0.15 mm was found to be the optimized road thickness resulting the highest tensile properties (E= 1.1 GPa; UTS= 36.8 MPa; Yield Strength= 24.4 MPa).

Figure 6. Impact test results for ABS cross ply and angle ply FDM specimens. Adapted from Fatimatuzahraa, Farahaina and Yusoff [31]

Figure 7. Impact strength and absorbed energy as a function of deposition speed for 5 wt% short carbon fiber reinforced ABS.
Other researchers focused on the optimization of mechanical properties of fiber-reinforced FDM parts. A method has been studied by few researchers to incorporate fibers or metal particles [14, 15]. This concept allows the gain in mechanical properties in comparison to unreinforced FDM parts. Authors, such as Zhong et al. [45] introduced short glass fibers to improve the mechanical properties of ABS filaments. They increased the glass fiber volume fraction to 13% and were able to reach tensile strengths up to 34% higher than the unreinforced ABS FDM parts. In another work, Shofner et al. [46] investigated an alternative approach to enhance the mechanical properties of FDM parts. They added vapor-grown carbon fibers in ABS, increasing the part’s tensile strength to over 45% in comparison with the unreinforced material.

Final Remarks

Additive manufacturing technologies are becoming relevant to important industries, such as aerospace and automotive. FDM is an AM technology that can bring benefits to manufacture lighter structures, a common goal for aircraft, spacecraft and car designers.

The majority of the published work has been focused on ABS, which is the most used polymer in FDM. Only a few studies have been performed on unreinforced and fiber-reinforced engineering thermoplastics, such as PEI and PEEK. Furthermore, most of the available studies have a limited scientific depthness focusing on the engineering optimization of part’s mechanical properties. There is a lack of scientific works addressing the correlations between the process parameters and part properties. Most of the reviewed studies reported that three process parameters - road thickness, deposition speed and air gap- play a central role in changing the mechanical properties. Negative air gap - i.e. the overlapping of adjacent roads – was shown to increase the tensile strength by improving part density. Increasing road thickness reduces the part density while faster deposition speeds improves the interlayer bonding.

In fact, FDM parts have not reached so far the mechanical properties of traditional manufacturing methods, such as injection molding. This is related to the presence of intrinsic voids between deposited roads.
Therefore, there is a vast niche for further process optimization. Examples are the development of new filament materials with short and long-fiber reinforcements [45, 47]. Therefore further research on new engineering-relevant materials is necessary to enable the understanding of the correlation among process-microstructure-properties in FDM, as well as its transfer to industry.

**Acknowledgment**

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**References**

38. Stratasys, ULTEM 9085.